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USE OF AN AIR-ASSIST FUEL NOZZLE TO REDUCE EXHAUST EMISSIONS FROM A GAS-TURBINE COMBUSTOR AT SIMULATED IDLE CONDITIONS

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16. Abstract

Tests were performed at typical engine idle conditions on a single J-57 combustor liner installed in a 30-cm- (12-in. -) diameter pipe to evaluate design modifications for reducing exhaust emissions. Using an air-assist fuel nozzle, the combustion efficiency was increased from 90.3 to 96.5 percent, and the total hydrocarbon and carbon monoxide exhaust emissions were reduced from 26.3 to 3.3 and from 51 to 40 g/kg of fuel burned, respectively. A corresponding increase in nitric oxide emissions from 0.8 to 1.5 g/kg of fuel burned was observed. Calculations performed for a complete landing-takeoff cycle of a typical engine indicated that the use of an air-assist nozzle during idle could decrease the total quantity of hydrocarbon and carbon monoxide emission by 69 and 20 percent, respectively, while nitric oxide would increase by 14 percent. The required secondary nozzle airflow amounts to less than 0.5 percent of the total engine airflow at idle.

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SUMMARY

Tests were performed on a single J-57 combustor liner installed in a 30-centimeter (12-in.) diameter pipe to evaluate design modifications for reducing exhaust emissions at engine idle conditions. Combustion efficiency and exhaust concentrations of total unburned hydrocarbons, carbon monoxide, and nitric oxide were measured for a typical idle condition at an inlet total pressure of 2 atmospheres, an inlet total temperature of 420 K (300° F), a reference velocity of 15 meters per second (50 ft/sec) and a range of fuel-air ratios of 0.004 to 0.015. The performance of six design modifications were evaluated and compared with the performance of the standard combustor. The best performance was obtained with a combustor using an air-assist fuel nozzle. At an idle fuel-air ratio of 0.008, the standard combustor had a combustion efficiency of 90.3 percent, and exhaust concentrations of total hydrocarbons and carbon monoxide of 26.3 and 51 grams per kilogram of fuel burned, respectively. Using an air-assist fuel nozzle for the same conditions, combustion efficiency was increased to 96.5 percent, and exhaust concentrations of total hydrocarbons and carbon monoxide were reduced to 3.3 and 40 grams per kilogram of fuel burned, respectively. A corresponding increase in the exhaust concentration of nitric oxide from 0.8 to 1.5 grams per kilogram of fuel burned was observed. Calculations performed for a complete landing-takeoff cycle of a typical engine indicate that the use of an air-assist nozzle during idle could decrease the total quantity of hydrocarbon and carbon monoxide emissions by 69 and 20 percent, respectively, while nitric oxide would increase by 14 percent. The required secondary nozzle airflow amounts to less than 0.5 percent of the total engine airflow at idle.

INTRODUCTION

References 1 to 3 clearly indicate that the major contribution to the pollution of the atmosphere by gas-turbine engines occurs in the vicinity of airports. The source of this pollution is due mostly to emissions of (1) smoke and nitric oxide during takeoff and landing and (2) unburned hydrocarbons and carbon monoxide during idle and taxi. The operation of aircraft at engine idle and taxi conditions results in a combustion efficiency that is much lower than that at takeoff and cruise, and therefore exhaust emissions of unburned hydrocarbons and carbon monoxide are significantly higher. Typical values for combustion efficiency at takeoff and cruise are 98 to 100 percent while at idle conditions, combustion efficiency may be well below 90 percent. The reasons for the low combustion efficiency at idle may be summarized as follows:

(1) The combustor inlet total pressure and temperature are relatively low because of the lower engine speed at idle.

(2) The combustor primary zone fuel-air ratio is lower than the optimum design value (near stoichiometric) established for the higher overall fuel-air ratios required at takeoff and cruise.

(3) Fuel atomization is generally poor at idle because the fuel nozzle pressure drop is at a minimum.

The purpose of this program was to investigate methods for altering combustor design in order to reduce exhaust emissions at idle conditions. In addition, the resulting improvement in combustion efficiency may significantly reduce total fuel consumption. Tests were conducted using a single J-57 combustor installed in a 30-centimeter (12-in.) diameter pipe. The performance of six design modifications were evaluated and compared with the performance of the standard combustor. The basic approach used to improve performance at idle was to (1) increase the overall primary zone fuel-air ratio, (2) increase the local primary zone fuel-air ratio in the vicinity of the fuel spray, or (3) improve fuel atomization. Performance was determined by measuring combustion efficiency and exhaust concentrations of total unburned hydrocarbons, carbon monoxide, and nitric oxide at typical idle conditions.

APPARATUS AND PROCEDURE

Facility

The test facility is shown in figure 1 and is described in reference 4. The test combustor is housed in a 30-centimeter (12-in.) diameter pipe. A nonvitiating preheater was used to obtain an inlet total temperature of 420 K (300° F). The test facility was connected to the laboratory air supply. Airflow rates and combustor pressures were regulated by remotely controlled valves upstream and downstream of the test section.

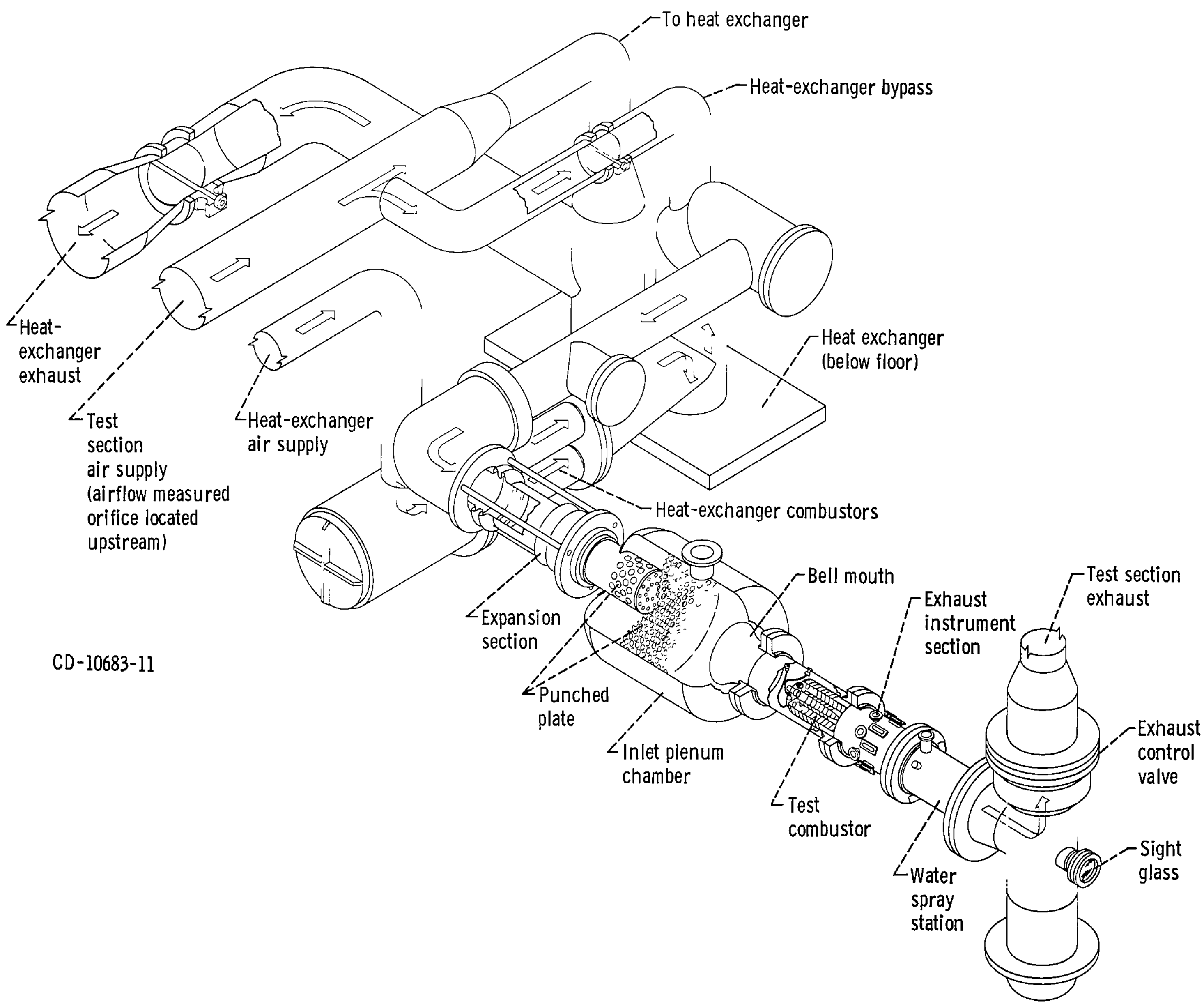
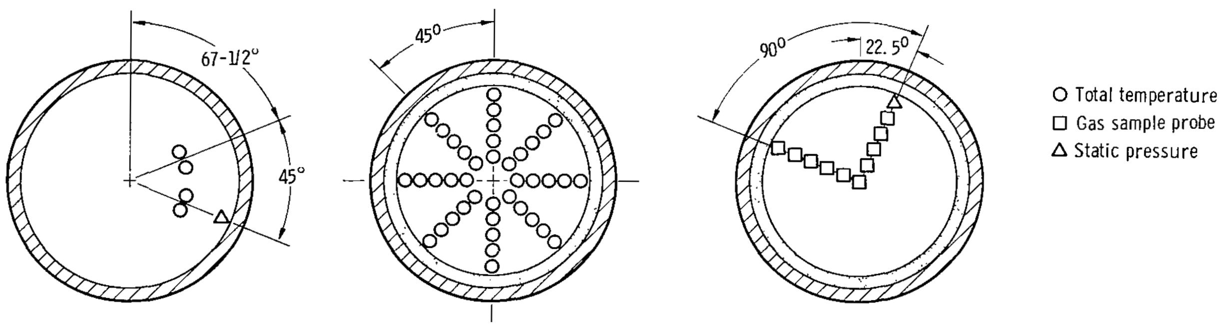


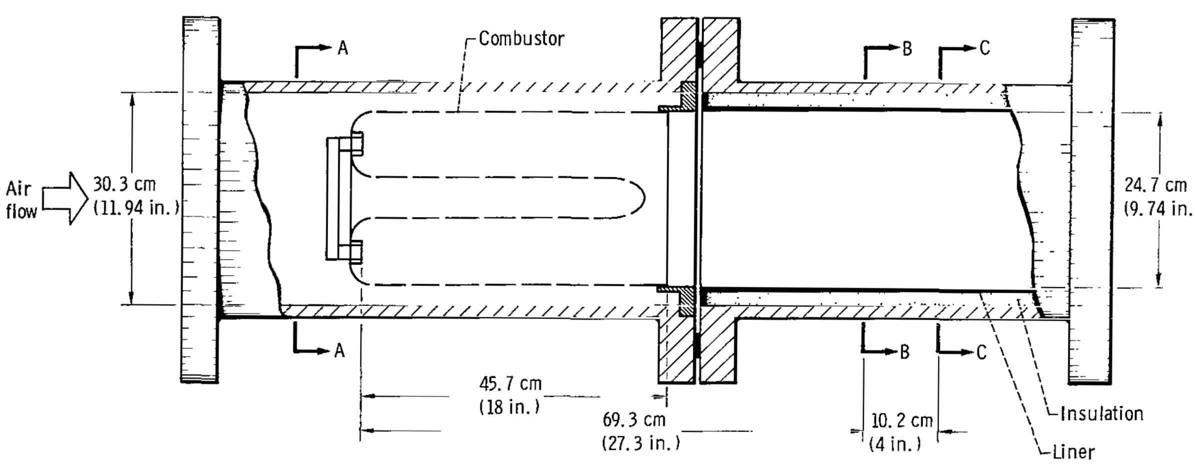
Figure 1. - Test installation.

Test Section

A cross section of the test section is shown in figure 2. The combustor reference area was defined as the cross-sectional area inside the 30-centimeter (12-in.) diameter test section which is 7.2×10^{-2} square meter ($0.775\ ft^2$) or approximately one-eighth the annular cross-sectional area of the combustor housing in the J-57 engine which contains eight combustor liners. To simplify fabrication, the inlet diffuser and the exit transition were made of constant area ducting of circular cross section.



(a) Instrumentation stations.



(b) Location of instrumentation at each station.

Figure 2. - Combustor test duct.

Combustor Modifications

Unless otherwise noted, tests were performed with the standard fuel nozzle manifold from the J-57 engine which consists of six dual-orifice nozzles (fig. 3). The combustor liner is shown in figure 4. Fuel-flows to the primary and secondary chambers of the dual-orifice nozzles were controlled by separate throttle valves. A typical flow calibration for these nozzles is shown in figure 5. Unless otherwise noted, fuel flows at idle operating conditions were obtained using only the primary orifice. The six modifications tested are described in table I.

The model 1 combustor had fuel flowing to alternate fuel nozzles so that only three of the six fuel nozzles were used. This modification increased the local fuel-air ratio in the vicinity of each of the three nozzles that were used. In addition, fuel atomization was improved by virtue of the higher pressure differential required to maintain idle fuel flow. In practice, this model simulates a combustor that would have a separate fuel manifold for idle operation.

The model 2 combustor was not specifically modified to reduce idle emissions, but instead was modified to reduce smoke emissions at takeoff conditions. This smoke reduction was accomplished by increasing primary zone airflow to reduce the primary zone fuel-air ratio. Model 2 is identical to the model 5G combustor described in reference 4. In this model, six slots having baffles in front of them were cut in the dome. A 1.9-centimeter (0.75-in.) diameter short tube was installed in line with each swirler except the swirler in line with the spark plug. The airflow through the nozzle shroud was also increased. Airflow to the primary zone was increased from about 25 to 35 percent of total airflow. Although this model had a satisfactory smoke number, altitude relight characteristics were poor. It would therefore be expected that the model 2 combustor would have lower combustion efficiency at idle conditions than even the standard combustor. This model is not meant to be representative of other designs with reduced smoke emissions but merely illustrates an extreme case as primary zone fuel-air ratio is reduced.

An air-assist fuel nozzle system was used in model 3. This was accomplished by connecting a source of high pressure air to the primary chamber of the standard fuel nozzle system in place of the primary fuel line. Fuel was introduced through the secondary orifice. The primary side airflow pressure differential was 150 newtons per square centimeter (220 psi). Figure 6 shows airflow as a function of nozzle pressure differential for both primary and secondary nozzles. At the pressure differential used, 0.15 percent of the combustor airflow was passed through the primary side of the fuel nozzle. In practice this would be accomplished by supercharging compressor bleed air and supplying it to the primary fuel nozzles at idle operation only.

Model 4 also consisted of an air-assist nozzle similar to model 3 except that high pressure air at 22 to 114 newtons per square centimeter (32 to 166 psi) was supplied to

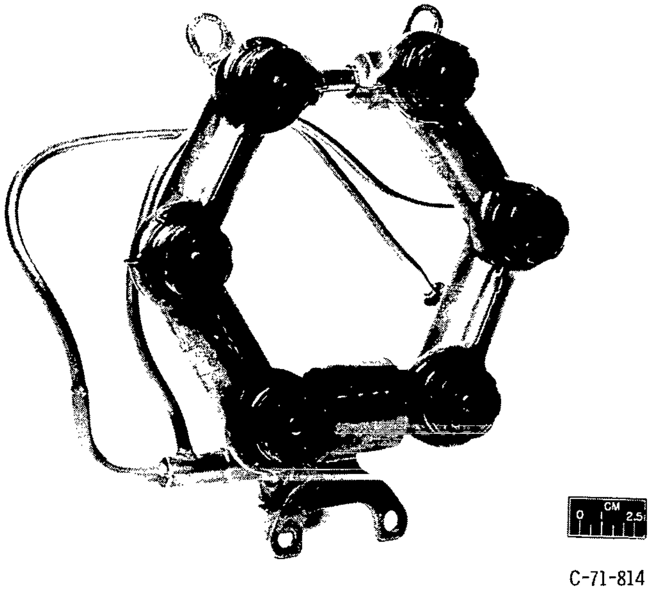
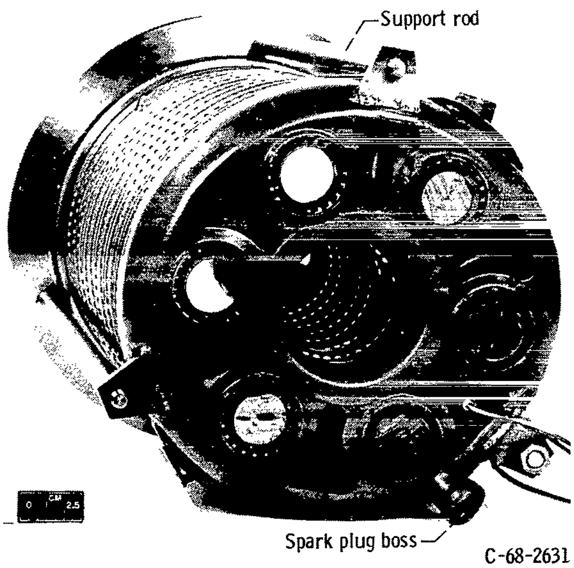
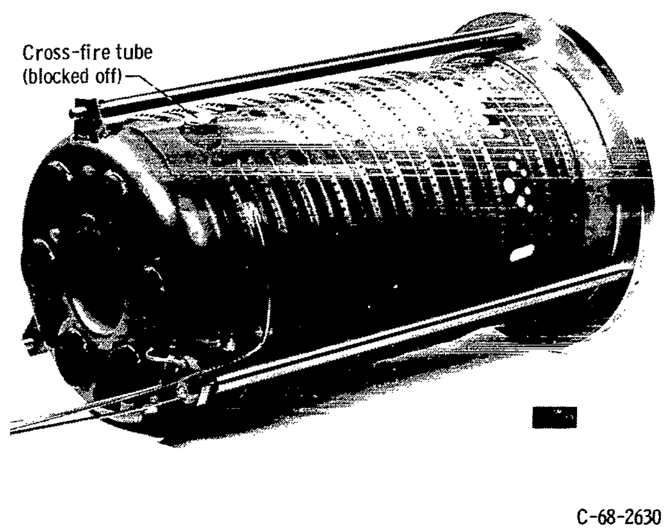


Figure 3. - Fuel nozzle manifold for test combustor.



(a) Upstream view.



(b) Side view.

Figure 4. - Combustor liner.

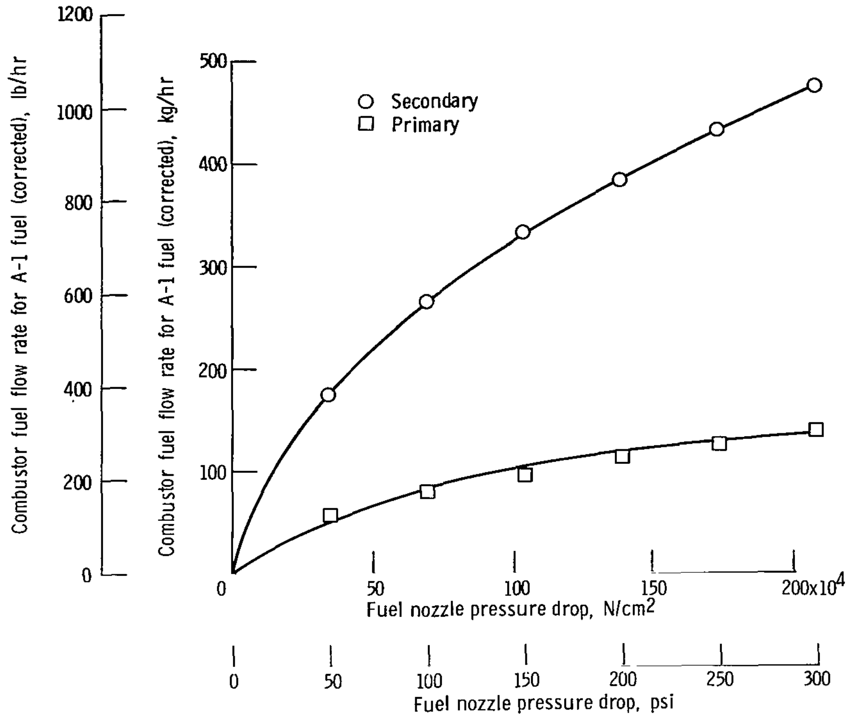


Figure 5. - Typical flow calibration for a set of six J-57 duplex fuel nozzles; calibration with water corrected to ASTM A-1 fuel density.

TABLE I. - COMBUSTOR MODIFICATIONS

Model	Description of modification	Physical change	Purpose
1	Alternate fuel nozzles blocked off	Increase local fuel-air ratio and improve fuel atomization	Increase combustion efficiency to reduce hydrocarbon and carbon monoxide emissions
2	Increased primary zone air entry ports	Reduce primary zone fuel-air ratio	Reduce smoke
3	Air-assist fuel nozzle; air through primary	Improve fuel atomization	Increase combustion efficiency to reduce hydrocarbon and carbon monoxide emissions
4	Air-assist fuel nozzle; air through secondary	Improve fuel atomization	Increase combustion efficiency to reduce hydrocarbon and carbon monoxide emissions
5	Air swirlers blocked	Increase primary zone fuel-air ratio	Increase combustion efficiency to reduce hydrocarbon and carbon monoxide emissions
6	Simplex orifice nozzles	Altered fuel spray pattern	Increase combustion efficiency to reduce hydrocarbon and carbon monoxide emissions

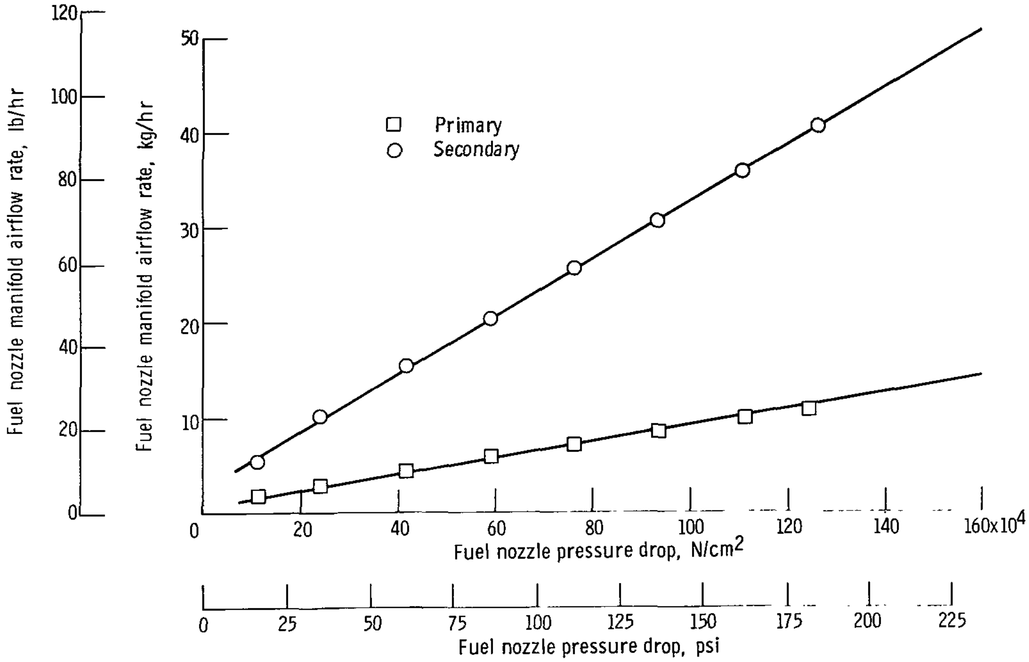


Figure 6. - Airflow calibration for J-57 fuel nozzle manifold.

the secondary side of the fuel nozzle while fuel was introduced through the primary side. For the range of pressure differentials used, 0.12 to 0.51 percent of the combustor airflow was passed through the secondary side of the fuel nozzle. This modification, in practice, would be accomplished by supercharging compressor bleed air and supplying it to the secondary fuel nozzles at idle operation only. For higher fuel flows, fuel would be introduced through the secondary orifice in the standard manner.

The air swirlers were blocked in model 5 to simulate a combustor with variable primary zone air entry geometry in order to increase the primary zone fuel-air ratio. Primary zone airflow was decreased from about 25 to 9 percent of total airflow. The swirler blockage would be removed for other-than-idle operation.

Simplex nozzles were used in the model 6 combustor instead of the dual-orifice nozzles used on the standard combustor. The nozzles used were Monarch series PLP with a 70° semisolid spray pattern. The flow rating was 13.2 liters per hour (3.5 gal/hr) at 69 newtons per square centimeter (100 psi). To compensate for the smaller diameter of the simplex nozzle, an annular spacer was installed between the simplex nozzle outer diameter and the swirler inner diameter. This modification simulated a change in the nozzle spray pattern.

Instrumentation

Airflows were measured by square edged orifices installed according to ASME specifications. Fuel flows were measured by turbine flowmeters. Pressures were measured by strain gage transducers.

The axial location of the test instrumentation planes are shown in figure 2(b). The cross-sectional positions of the gas sampling probes, thermocouples, and combustor static pressure taps are shown in figure 2(a). Exit temperatures were measured by 40 bare junction Chromel-Alumel thermocouples positioned at the center of equal areas as shown in figure 2(a).

Exhaust Emission Probe

The exhaust emission probe, which is water-cooled, is shown in figure 7. The probe was designed to sample the exhaust stream at five positions at the centers of equal areas. Two probes, positioned at 90° from each other, were used to gather a sample as shown in figure 2(a). All five sampling positions of each probe were connected together in a

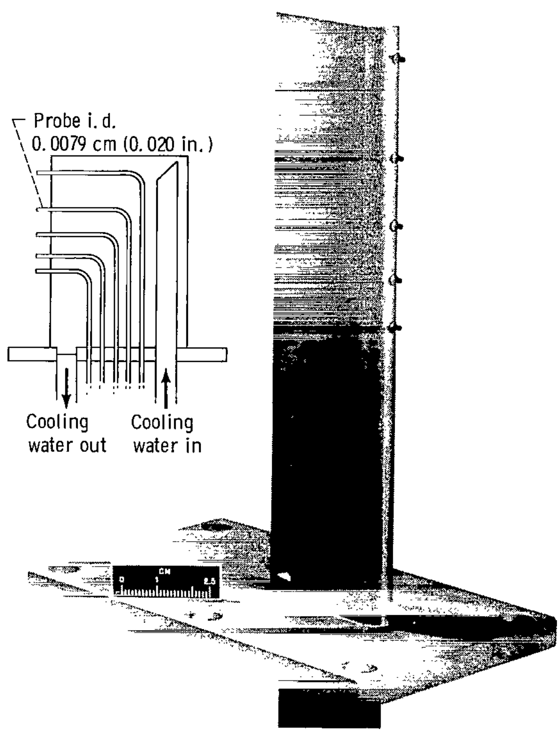


Figure 7. - Exhaust emission probe.

manifold outside the test section, and the sample flows of the two probes were also manifolded together. The sampling line length was about 9 meters (30 ft). The temperature of the sample line was maintained at 480 K (400° F). The emission sample was analyzed for total hydrocarbon content by an on-line Beckman Model 106E flame ionization detector. The flame ionization cell temperature was 370 K (220° F). Batch samples for gas analysis were collected for carbon monoxide in 150- or 300-milliliter stainless steel vessels and for nitric oxide in 250- or 300-milliliter glass vessels. The content of these vessels were analyzed at a later date. Carbon monoxide content of the exhaust sample was determined using a Beckman Model GC-4 gas chromatograph. Nitric-oxide content was found using the Saltzman method described in reference 5.

Test Conditions

Tests were conducted over a range of fuel-air ratios at simulated idle conditions of 2 atmospheres inlet total pressure, 420 K (300° F) inlet temperature, and 15 meters per second (50 ft/sec) reference velocity. Some data were also taken at 370 K (200° F) inlet total temperature. The fuel used was ASTM A-1 with an average hydrogen-carbon ratio of 0.161 and a lower heating value of 43 200 joules per gram (18 600 Btu/lb).

RESULTS AND DISCUSSION

Combustor Evaluation

Combustion efficiency and exhaust emission data will be compared for the standard combustor and six modifications. Test results are shown in table II.

Combustion Efficiency

Combustion efficiency is defined as the ratio of actual temperature rise, as determined by averaging the 40 exit thermocouples, to the theoretical temperature rise for ASTM A-1 fuel as determined by the fuel-air ratio and the inlet total temperature and pressure. The effects of each modification on combustion efficiency are shown in figure 8. Large decreases in efficiency at fuel-air ratios below about 0.008 are partly attributed to poor fuel atomization due to nozzle pressure differential falling below 34 newtons per square centimeter (50 psi), which is considered to be the minimum pressure for sufficient atomization. The tailed symbols in figure 8 indicate a nozzle pressure drop of

TABLE II. - TEST RESULTS

(a) All data at simulated idle conditions: inlet pressure, 2 atmospheres; inlet temperature, 420 K (300° F); reference velocity, 15 meters per second (50 ft/sec); airflow, 1.87 kilograms per second (4.14 lb/sec)

Model	Fuel-air ratio	Exhaust emissions						Combustion efficiency	Exit temperature		Fuel nozzle pressure differential		Primary-nozzle airflow pressure differential		Secondary-nozzle airflow pressure differential	
		Hydrocarbons		Carbon monoxide		Nitric oxide			K	°F						
		g/kg fuel	ppm	g/kg fuel	ppm	g/kg fuel	ppm				N/cm^2	psi	N/cm^2	psi	N/cm^2	psi
Standard	0.0050	46.7	481	193	995	0.42	2	44.5	507	452	7.16	10.4	---	---	-----	-----
	.0080	26.3	432	50.9	418	.78	6	90.3	707	812	34.6	50.3	---	---	-----	-----
	.0148	12.1	365	50.7	765	.35	5	95.9	965	1276	123	178	---	---	-----	-----
1	0.0046	35.1	333	34.0	161	0.68	3	51.8	511	459	19.6	28.4	---	---	-----	-----
	.0083	20.1	343	80.9	690	1.13	9	87.8	707	813	126	183	---	---	-----	-----
	.0158	4.19	135	31.9	514	1.46	22	95.9	994	1329	441	641	---	---	-----	-----
2	0.0042	60.4	523	135	585	0.17	0.7	50.0	503	446	10.5	15.2	---	---	-----	-----
	.0080	38.0	624	154	1340	.13	1	61.3	647	704	49.3	71.5	---	---	-----	-----
	.0155	7.27	230	57.4	907	.81	12	92.3	966	1278	190	213	---	---	-----	-----
3	0.0042	10.5	91	15.2	66	1.48	6	82.8	563	553	1.65	2.4	150	218	-----	-----
	.0079	6.71	109	27.9	227	1.19	9	96.7	725	845	3.44	5.0	151	219	-----	-----
	.0146	6.37	190	43.1	642	.86	12	97.7	967	1280	15.0	20.8	152	219	-----	-----
4	0.0042	7.16	62	27.5	119	1.48	6	87.3	572	569	10.1	14.7	---	---	114	166
	.0082	3.32	56	39.9	336	1.53	12	96.5	737	866	40.4	59.6	---	---	114	166
	.0153	1.35	42	21.4	334	1.17	17	96.6	985	1313	140	203	---	---	112	163
	.0046	33.5	318	36.7	174	1.58	7	87.9	583	590	12.3	17.8	---	---	21.7	31.5
	.0044	26.0	236	22.9	104	1.42	6	95.1	588	598	12.8	18.6	---	---	46.9	68.1
	.0044	20.7	188	29.3	133	1.65	7	94.9	591	604	14.2	16.0	---	---	102	148
	.0084	13.2	228	65.8	568	.99	8	97.2	754	897	45.1	65.6	---	---	20.7	30.1
	.0083	9.44	161	35.1	299	1.38	11	98.8	757	903	44.0	64.0	---	---	53.1	77.0
	.0083	7.86	134	35.1	299	1.76	14	100.6	754	897	43.1	62.6	---	---	100	146
5	0.0040	110	912	49.2	203	0.52	2	50.5	509	456	87.5	12.7	---	---	-----	-----
	.0079	36.3	590	52.1	423	.79	6	93.9	724	843	35.0	50.9	---	---	-----	-----
	.0151	8.11	250	42.1	646	.90	13	98.1	991	1323	115	167	---	---	-----	-----
6	0.0040	58.1	480	92.6	382	0.52	2	52.2	516	468	11.5	16.7	---	---	-----	-----
	.0083	22.5	384	110	940	.63	5	89.7	723	841	26.8	38.9	---	---	-----	-----
	.0156	4.68	146	40.6	646	.61	9	94.3	985	1313	116	168	---	---	-----	-----

(b) All data at simulated idle conditions: inlet pressure, 2 atmospheres; inlet temperature, 366 K (200° F); reference velocity, 15 meters per second (50 ft/sec); airflow, 2.15 kilograms per second (4.75 lb/sec)

Model	Fuel-air ratio	Exhaust emissions						Combustion efficiency	Exit temperature		Fuel nozzle pressure differential		Primary-nozzle airflow pressure differential		Secondary-nozzle airflow pressure differential	
		Hydrocarbons		Carbon monoxide		Nitric oxide			K	°F						
		g/kg fuel	ppm	g/kg fuel	ppm	g/kg fuel	ppm				N/cm^2	psi	N/cm^2	psi	N/cm^2	psi
Standard	0.0085	31.6	552	92.6	808	0.61	5	92.3	677	758	58.5	85.0	---	---	-----	-----
4	.0084	7.42	128	60.9	525	1.49	12	96.8	694	790	58.1	84.3	---	---	102	148

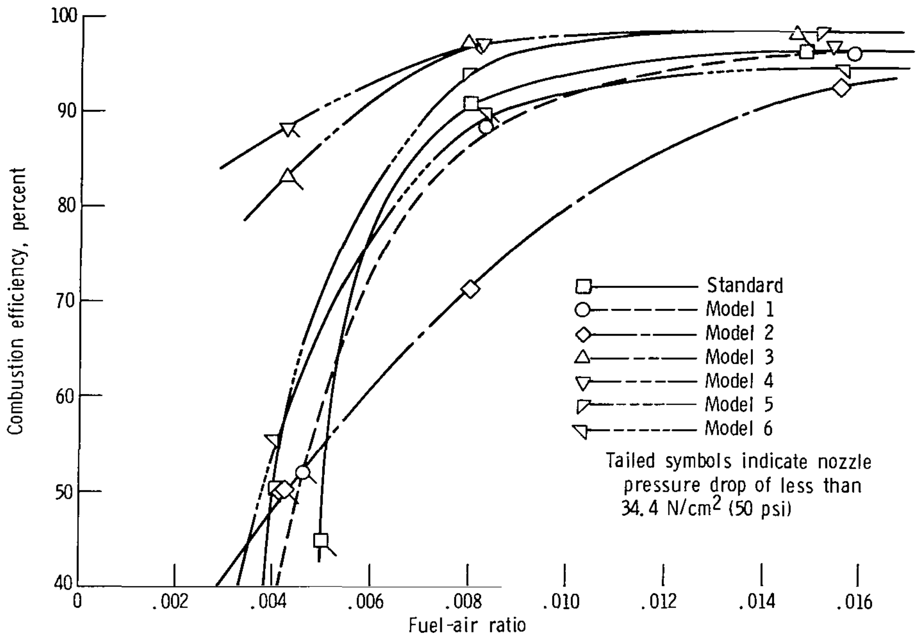


Figure 8. - Variation of combustion efficiency with fuel-air ratio. Reference velocity, 15 meters per second (50 ft/sec); inlet total pressure, 2 atmospheres, inlet total temperature, 420 K (300° F).

less than 34 newtons per square centimeter (50 psi). The modifications with the air-assist nozzles (models 3 and 4) produced the biggest improvement in combustion efficiency. The percentage improvement of models 3 and 4 became greater as fuel-air ratio was decreased. The air-assist flow pressure differential was 151 newtons per square centimeter (219 psi) for model 3 and 114 newtons per square centimeter (166 psi) for model 4. At a fuel-air ratio of 0.008, the combustion efficiency was improved from 90.3 percent for the standard combustor to 96.7 percent for model 3 and 96.5 percent for model 4. The lowest combustion efficiency at a fuel-air ratio of 0.008 was obtained with model 2. This low efficiency of 61 percent was due to the low primary zone fuel-air ratio in model 2. Although model 1 had a relatively high fuel nozzle pressure drop of 126 newtons per square centimeter (183 psi) at a fuel-air ratio of 0.0083, the combustion efficiency was still slightly below that of the standard combustor at this fuel-air ratio. Some improvement in efficiency over the standard combustor was obtained with the model 5 combustor at a fuel-air ratio of 0.008. No improvement was noted for the model 6 combustor.

Total Hydrocarbons

Total hydrocarbons emission data are shown plotted in figure 9. Emission index is defined as grams of emission per kilogram of fuel burned. As expected from the combus-

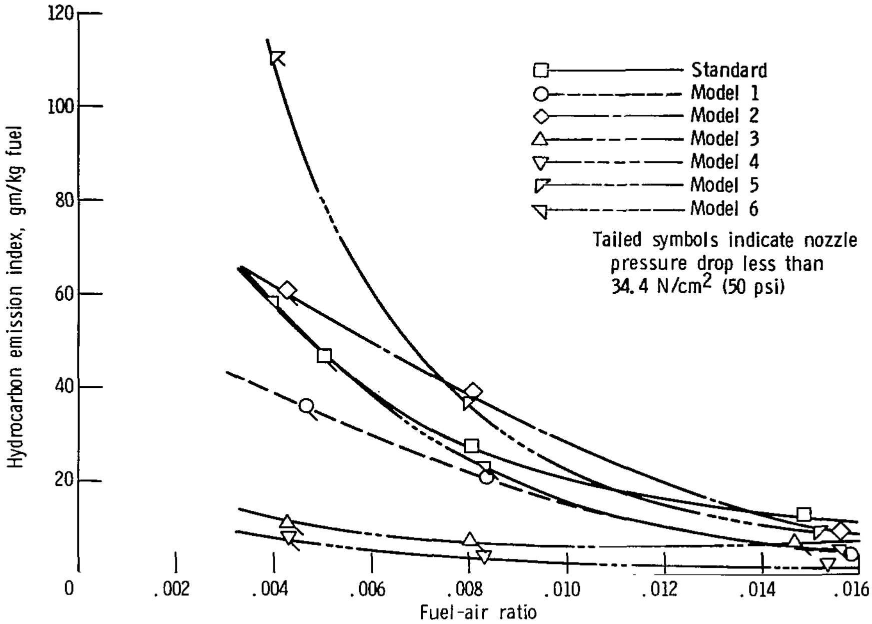


Figure 9. - Variation of hydrocarbon emission index with fuel-air ratio. Reference velocity, 15 meters per second (50 ft/sec); inlet total pressure, 2 atmospheres; inlet total temperature, 420 K (300° F).

tion efficiency results presented in figure 8, the only modifications that provided a large reduction in hydrocarbon emission index were models 3 and 4. Total hydrocarbon emission at a fuel-air ratio of 0.008 varied from about 38 grams per kilogram fuel for models 2 and 5 to 6.7 grams per kilogram fuel for model 3 and 3.3 grams per kilogram fuel for model 4. The standard combustor had a hydrocarbon emission index of 26.3 grams per kilogram fuel at a fuel-air ratio of 0.008. The high emission index for model 5 at a fuel-air ratio of 0.004 is probably due to poor mixing at low fuel-air ratios.

Carbon Monoxide

Carbon monoxide emission data are shown in figure 10. Choosing a fuel-air ratio of 0.008, the carbon monoxide emission index ranged from a high of 154 grams per kilogram fuel for the model 2 combustor to lows of 40 grams per kilogram fuel for the model 4 combustor and 28 grams per kilogram fuel for the model 3 combustor. The standard combustor had a carbon monoxide emission index of 51 grams per kilogram at a fuel-air ratio of 0.008. For the range of fuel-air ratios shown in figure 10, models 3 and 4 had substantially lower emissions than the other models tested. The high carbon monoxide emission index for the standard combustor at the low fuel-air ratio is consistent with its low efficiency at this condition.

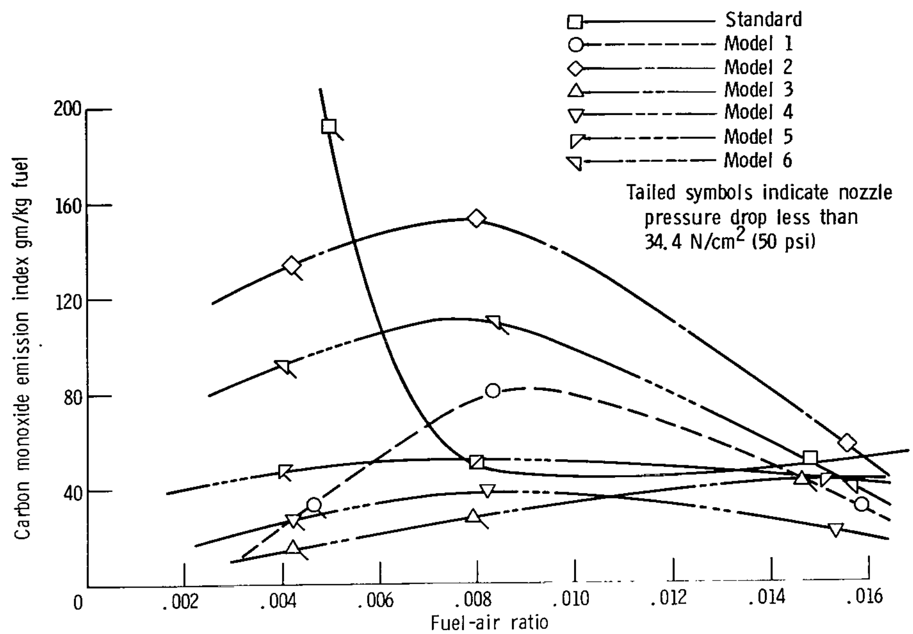


Figure 10. - Variation of carbon monoxide emission index with fuel-air ratio. Reference velocity, 15 meters per second (50 ft/sec); inlet total pressure, 2 atmospheres; inlet temperature, 420 K (300^0 F).

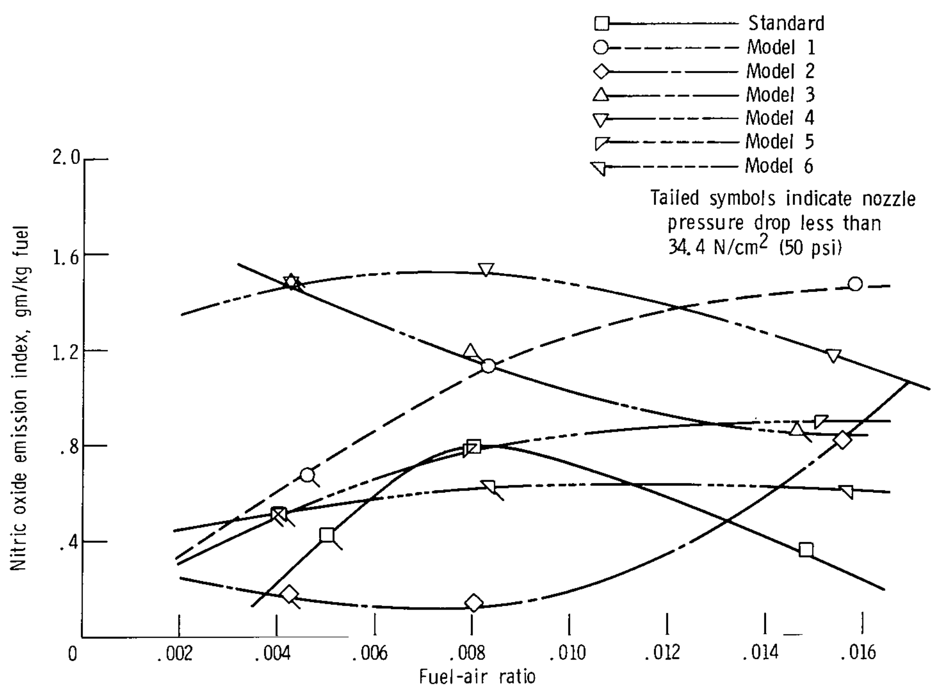


Figure 11. - Variation of nitric oxide emission index with fuel-air ratio. Reference velocity, 15 meters per second (50 ft/sec); inlet total pressure, 2 atmospheres; inlet temperature, 420 K (300^0 F).

Nitric Oxide

The emission data for nitric oxide are shown in figure 11. All data are below an emission index of 2 for the range of fuel-air ratios tested. At a fuel-air ratio of 0.008 the model 4 combustor had the highest emission index of 1.5. Model 2 had the lowest emission (0.1 g/kg fuel) at a fuel-air ratio of 0.008. This low emission in the model 2 combustor is due to the low primary zone fuel-air ratio. The increase in nitric oxide emission of models 3 and 4 over the standard combustor was attributed to an increase in the rate of formation of nitric oxide due to an increase in reaction zone temperature because of higher combustion efficiency. Reference 2 indicates that typical aircraft gas turbine engines at idle and takeoff have nitric oxide emission indexes of 2.0 and 4.3, respectively.

Effect of Air-Assist Nozzle Pressure Differential

A series of tests were made with the model 4 combustor over a range of air-assist nozzle pressure differentials in an effort to determine how much air-assist flow was required to effect a substantial change in combustion efficiency and exhaust emissions. The results of these tests are shown in figures 12 to 15.

The variation in combustion efficiency with secondary fuel nozzle airflow pressure differential is shown in figure 12. For a fuel-air ratio of 0.008, a pressure differential of 40 newtons per square centimeter (58 psi) is sufficient to increase combustion efficiency from 90.3 to 98.5 percent. This represents 0.2 percent of the combustor total airflow. The drop in efficiency at 120 newtons per square centimeter is within the accuracy of the efficiency calculations. At an inlet total temperature of 370 K (200° F) and a fuel-air ratio of 0.008, the combustion efficiency increased from 92.3 percent with no secondary airflow to 96.8 percent with an air-assist nozzle pressure drop of 102 newtons per square centimeter (148 psi).

Variations of hydrocarbon emission index with secondary nozzle airflow pressure differential are shown in figure 13. At a fuel-air ratio of 0.008, a pressure differential of 70 newtons per square centimter (102 psi) is required to reduce the hydrocarbon emission index from 27 grams per kilogram fuel to 6 grams per kilogram fuel. This airflow represents 0.3 percent of total combustor airflow. At an inlet total temperature of 370 K (200° F) and a fuel-air ratio of 0.008, the hydrocarbon emission index was reduced from 32 grams per kilogram fuel to 7.4 grams per kilogram fuel with an air-assist nozzle pressure differential of 102 newtons per square centimeter (148 psi).

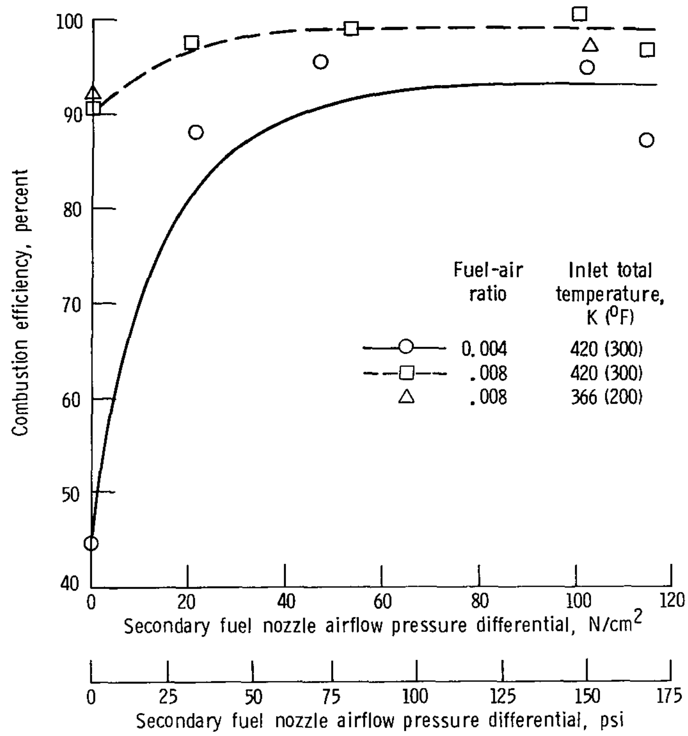


Figure 12. - Variation of combustion efficiency with secondary fuel nozzle airflow pressure differential. Inlet pressure, 2 atmospheres; reference velocity, 15 meters per second (50 ft/sec).

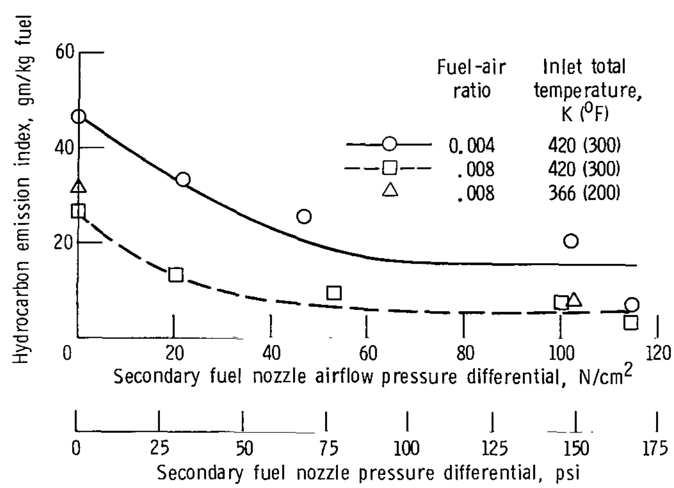


Figure 13. - Variation of hydrocarbon emission index with secondary fuel nozzle airflow pressure differential. Inlet pressure, 2 atmospheres; reference velocity, 15 meters per second (50 ft/sec).

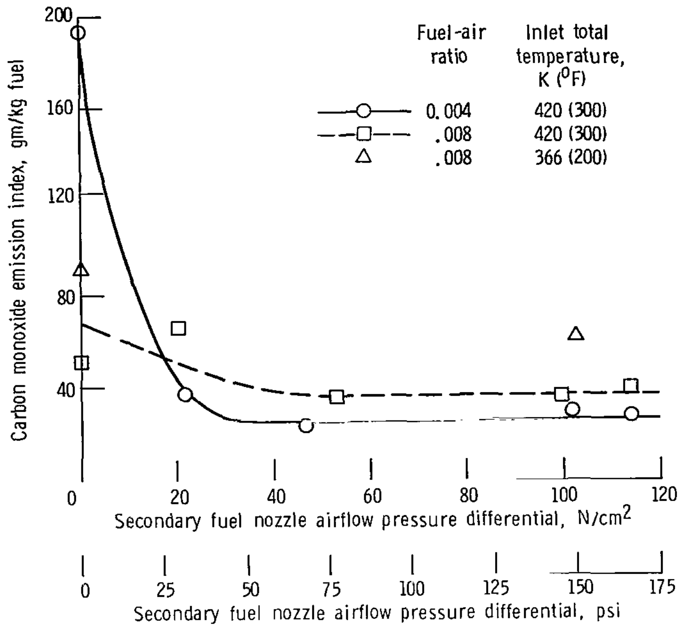


Figure 14. - Variation of carbon monoxide emission index with secondary fuel nozzle airflow pressure differential. Inlet pressure, 2 atmospheres; reference velocity, 15 meters per second (50 ft/sec).

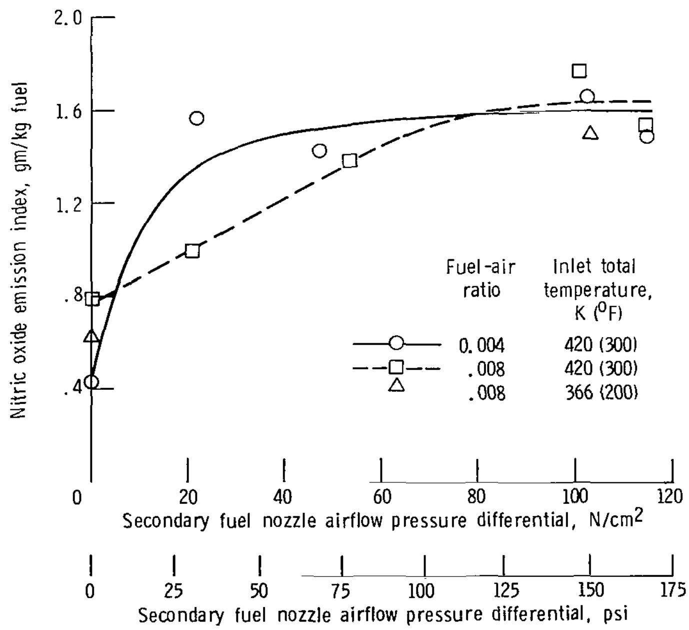


Figure 15. - Variation of nitric oxide emission index with secondary fuel nozzle airflow pressure differential. Inlet pressure, 2 atmospheres; reference velocity, 15 meters per second (50 ft/sec).

Carbon monoxide emission index is shown plotted against secondary fuel nozzle airflow pressure differential in figure 14. For a fuel-air ratio of 0.008 a secondary airflow pressure differential of 40 newtons per square centimeter (58 psi) is required to reduce the carbon monoxide emission from 70 grams per kilogram fuel to 37 grams per kilogram fuel. At an inlet total temperature of 370 K (200° F) and a fuel-air ratio of 0.008, the carbon monoxide emission index was reduced from 93 kilograms per gram fuel to 61 grams per kilogram fuel with a nozzle pressure differential of 102 newtons per square centimeter (148 psi).

A plot of nitric oxide emission index against secondary nozzle airflow pressure differential is shown in figure 15. There is a trend toward increasing nitric oxide emission with increasing secondary nozzle airflow pressure differential (although emission index levels off at about 60 N/cm^2) because more efficient fuel atomization results in higher combustion efficiency thereby increasing the temperature in the primary zone and increasing the rate of nitric oxide formation.

SUMMARY OF RESULTS

A series of modifications and a standard production of J-57 combustor were tested at simulated idle conditions, and comparisons made of combustion efficiency and total hydrocarbons, carbon monoxide, and nitric oxide emissions. The models with the best performance were those having air-assist fuel nozzles. The combustor with air-assist flowing through the secondary side of the fuel nozzle had the following performance comparison with the standard combustor at simulated idle conditions (inlet total pressure, 2 atm; inlet total temperature, 420 K (300° F); reference velocity, 15 m/sec (50 ft/sec); fuel-air ratio, 0.008):

1. Combustion efficiency was increased from 90.3 to 96.5 percent.

2. Total hydrocarbon emission index was decreased from 26.3 to 3.3 grams per kilogram fuel.

3. Carbon monoxide emission index was decreased from 51 to 40 grams per kilogram fuel.

4. Nitric oxide emission index was increased from 0.8 to 1.5 grams per kilogram fuel.

5. To obtain substantial performance increases, a secondary airflow pressure differential as low as 40 newtons per square centimeter (58 psi) was required.

6. The secondary nozzle airflow required at a pressure differential of 40 newtons per square centimeter (58 psi) represents 0.2 percent of the total combustor airflow.

APPLICATION OF RESULTS

Application of air-assist fuel nozzles to present day production turbojet engines for use during idle operation could substantially improve combustion efficiency and reduce total hydrocarbon and carbon monoxide emissions. The tests described herein were made with the standard dual-orifice fuel nozzles with air flowing through the secondary side. It is possible that, if special nozzles were designed for air-assist operation during idle operation, performance improvements could be even greater. No attempt was made to assess the problem of incorporating this design modification into a typical turbojet engine.

Calculations were performed in order to predict the overall change in the quantity of pollutants emitted into the atmosphere during landing and takeoff operations of a typical turbojet engine after installing an air-assist fuel nozzle system for idle operation. Data on fuel consumption of a JT3D engine during taxi, idle, landing, takeoff, approach, and climbout were obtained from reference 2. The landing-takeoff (LTO) cycle is defined to include operations below an altitude of 900 meters (3000 ft).

Corresponding emission indexes for a JT3D for the various operating phases of the LTO cycle were also obtained from reference 2. These data were then used to calculate the quantities of carbon monoxide, total hydrocarbons, and nitric oxide emitted per engine during (1) taxi and idle, (2) approach, and (3) takeoff, landing, and climbout. These results are presented in table III.

Corresponding emission quantities were then calculated for the same engine assuming the installation of an air-assist fuel system for idle operation. These calculations were performed by multiplying the emission indexes given in reference 2 for the JT3D engine at idle and taxi by the ratios of the experimental emission indexes obtained in this program for the model 4 of the standard J-57 combustor. These results are also presented in table III. Hydrocarbon emissions were reduced from 10.2 to 3.18 kilograms (22.5 to 7.02 lb), a reduction of 69 percent. Carbon monoxide was reduced from 19.9 to 16.0 kilograms (43.9 to 35.2 lb), a reduction of 20 percent. Nitric oxide

TABLE III. - EMISSION COMPARISON FOR A TYPICAL TURBOJET ENGINE OPERATED OVER AN LTO CYCLE, WITH AND WITHOUT AIR ASSIST FUEL NOZZLES

Operational mode	Fuel consumed per engine (a)		Emission indexes for unmodified combustor, g/kg fuel (b)			Pollutant produced by unmodified combustor						Emission indexes for air-assist combustor, g/kg fuel			Pollutant produced by air-assist combustor					
						Hydrocarbons		Carbon monoxide		Nitric oxide					Hydro carbons		Carbon monoxide		Nitric oxide	
	kg	lb	Hydrocarbons	Carbon monoxide	Nitric oxide	kg	lb	kg	lb	kg	lb	Hydro carbons	Carbon monoxide	Nitric oxide	kg	lb	kg	lb	kg	lb
Taxi and idle	106.8	235.5	75.0	174	2.00	8.03	17.7	18.6	41.0	0.21	0.47	9.40	137	3.93	1.00	2.20	14.7	32.3	0.42	0.92
Approach	135.3	298.2	16.0	8.70	2.70	2.16	4.77	1.18	2.60	.36	.80	16.0	8.70	2.70	2.16	4.77	1.18	2.60	.36	.80
Takeoff, landing, and climbout	215.0	473.9	.10	.70	4.30	.02	.05	.15	.33	.93	2.04	.10	.70	4.30	.02	.05	.15	.33	.93	2.04
Total	457.1	1007.6	----	------	----	10.2	22.5	19.9	43.9	1.50	3.31	-----	------	----	3.18	7.02	16.0	35.2	1.71	3.76

[a]Obtained from table 36 of ref. 2.
[b]Obtained from table 40 of ref. 2.

emissions were increased from 1.50 to 1.71 kilograms (3.31 to 3.76 lb), an increase of 14 percent. As was previously explained, the increase in nitric oxide emissions is a result of the increased combustion efficiency.

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